

Design of a Capacitive LTCC-based Pressure Sensor

Darko Belavič¹⁾, Marina Santo Zarnik¹⁾, Cristina Marghescu²⁾, Ciprian Ionescu²⁾, Paul Svasta²⁾, Marko Hrovat³⁾, Srečko Maček³⁾, Igor Lipušček⁴⁾, and Sandi Kocjan⁴⁾

¹⁾HIPOT-RR, Trubarjeva 7, 8310 Šentjernej, Slovenia,

²⁾University “Politehnica” of Bucharest, Spl. Independentei 313, 060042-Bucharest, Romania

³⁾Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

⁴⁾HYB, Levičnikova 34, 8310 Šentjernej, Slovenia

Email address of corresponding author: darko.belavic@ijs.si

Abstract: *A capacitive pressure sensor was realized by using low-temperature co-fired ceramic (LTCC) materials and technology. The paper will present the design considerations of a sensing element, and compares the experimental data to the theoretical design, with the aim to improve the sensor's characteristics. Special points of attention are the linearity, the temperature behaviour, the pressure media and the behaviour of the reference pressure medium.*

1. INTRODUCTION

Most pressure sensors are made by micro-machining silicon. On the other hand, complex sensor systems combine different materials (silicon, ceramic, metal, polymer, etc.) and technologies (semiconductor, thin and thick film, etc.). In some demanding applications, thick-film technology and ceramic materials are a very useful alternative [1-3].

Ceramic pressure sensors have been available for more than 25 years. Most of them are used for measuring pressure ranges higher than 100 kPa. In comparison with semiconductor sensors they are larger, more robust and have a lower sensitivity. Some new technologies developed within the past few years offer a feasible solution for replacing the silicon-based pressure sensor in some applications. One of these technologies is low-temperature cofired ceramic (LTCC) technology [3-5].

Capacitive sensors are suitable for low-pressure ranges and low-power applications [6]. The main disadvantage is the presence of different, disturbing parasitic elements. This contribution includes the study of the sensing element for the capacitive pressure sensor, and designing a capacitive pressure sensor using thick-film and LTCC materials and technology. Special attention is focused on the design of the sensing element to improve the sensor's characteristics.

2. MATERIAL AND CONSTRUCTION

Low-temperature cofired ceramic (LTCC) technology is a three-dimensional ceramic technology for the fabrication of different electronic modules. It is a mixture of thick-film and ceramic technologies. The thick-film technology contributes the lateral and vertical electrical interconnections, and the embedded and surface passive electronic components (resistors, thermistors, inductors, capacitors). The laminate ceramic technology contributes the electrical, mechanical and dielectric properties as well as different three-dimensional (3D) structures, such as cantilevers, bridges, diaphragms, channels and cavities [7-11]. The LTCC materials consist of ceramic and glass particles suspended in an organic binder. The materials are either based on crystallisable glass or a mixture of glass and ceramics. The LTCC materials before sintering are soft and flexible sheets or tapes called green sheets or green tapes. Different thicknesses, from a few tens of μm to a few hundreds of μm , of green tapes are commercially available on the market. Green tapes are easily handled and mechanically shaped. On the separate tapes the thick-film layers are screen-printed and then stacked and laminated together with hot pressing. A large number of layers (tapes) can form high-density interconnections and 3D structures. These laminates are then sintered in a one-step process (called cofiring) at relatively low

temperatures (850–900°C) to form a rigid monolithic ceramic multilayer module (an electronic circuit and/or a 3D microstructure). The whole LTCC process saves time, money and reduces the circuit's dimensions, compared with conventional hybrid thick-film technology [12]. The important advantages of LTCC materials in comparison with alumina are an about three times lower Young's modulus and flexibility in the 3D designing. Some of the characteristics of fired LTCC laminates and alumina substrates are presented in Table 1.

Characteristics	LTCC	Al ₂ O ₃ 94-99.5%
Thermal expansion coeffi. (10 ⁻⁶ /K)	5.8-7.0	7.6-8.3
Density (g/cm ²)	2.5-3.2	3.7-3.9
Flexural strength (MPa)	170-320	300-460
Young's modulus (GPa)	90-110	215-415
Poisson's ratio	0.17	0.23
Thermal conductivity (Wm/K)	2.0-4.5	20-26
Dielectric constant	7.5-8.0	9.2-9.8
Loss tg (x10 ⁻³)	1.5-2.0	0.5
Resistivity (ohm.cm)	10 ¹² -10 ¹⁴	10 ¹² -10 ¹⁴
Breakdown (V/100 μm)	>4000	3000-4000

Tab. 1. Some characteristics of LTCC material in comparison with Al₂O₃ ceramics [12]

Most ceramic pressure sensors are made with deformable diaphragms [5]. The deformation is induced by the applied pressure and then converted into an electrical signal. LTCC technology and materials are suitable for forming a three-dimensional (3D) construction, consisting of a circular edge-clamped deformable diaphragm that is bonded to a rigid ring and a base substrate. These elements form the cavity of the pressure sensor. The cross-section of the ceramic pressure sensor is shown in Figure 1.

The deformation (i.e., the deflection) of the diaphragm induced by the applied pressure depends on the construction, the dimensions and the material properties (Table 1) of the sensor body [5,12]. The influence of the geometry and the material properties of the LTCC structure on the deflection of an edge-clamped deformable diaphragm under an applied pressure is described by equation (1)

$$y(r) = \frac{3P(1-\nu^2)(R^2 - r^2)^2}{16Et^3} \quad (1)$$

where the deflection y at the position r from the centre of the diaphragm is a function of the applied pressure, P , the material characteristics (elasticity, E , and Poisson's ratio, ν) of the diaphragm, and the dimensions (thickness, t , and radius, R) of the diaphragm (Figure 1).

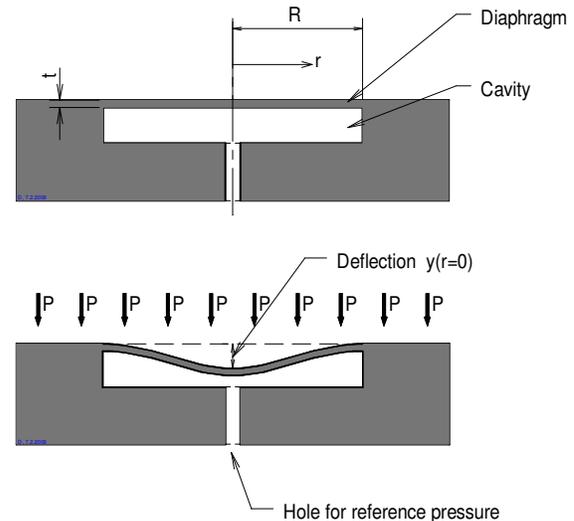


Fig. 1. The schematic cross-section of the LTCC structure of a ceramic pressure sensor (not to scale)

3. CAPACITIVE PRESSURE-SENSOR THEORY

The capacitive pressure sensor is based on the fractional change in capacitance ($\Delta C/C$) induced by the applied pressure. The basic element of a capacitive pressure sensor is an equivalent parallel-plate air-gap capacitor with clamped edges [6,13,14], as shown in Figure 2. The construction of the LTCC-based ceramic capacitive pressure sensor is very similar to other ceramic pressure sensors. This structure consists of a circular, edge-clamped deformable diaphragm that is bonded to a rigid ring and the base substrate. These elements then form the cavity of the pressure sensor. The cavity has an inlet for a reference pressure, which is in most cases ambient air. A specific feature of the capacitive pressure sensor is that the distance between the deformable diaphragm and the rigid base substrate is smaller and must be very well defined. A second specific feature is that the bottom electrode is deposited on the rigid substrate and the upper electrode of the capacitor is deposited on the deformable diaphragm [15-17].

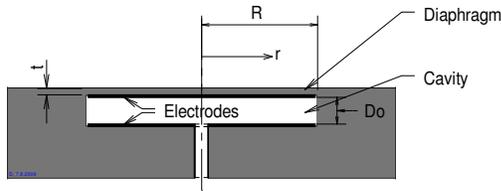


Fig. 2. The cross-section of a capacitive pressure sensor (not to scale)

The value of the initial capacitance (C_0) of the capacitive pressure sensor, neglecting all additional fringing capacitances, is expressed as:

$$C_0 = \epsilon_0 \cdot \epsilon_r \cdot \frac{A}{D_0} \quad (2)$$

where ϵ_0 is the permittivity in vacuum, ϵ_r is the relative permittivity of the media between the two plates, A is the area of the electrode plate, and D_0 is the gap spacing between the two plates.

When the applied pressure is within the nominal range and when the deflection of the diaphragm $y(r=0)$ is much smaller than both the thickness of the diaphragm and the distance between the electrodes, then the capacitance between the electrodes is given by equation (3) [15-17].

$$C(P) = \epsilon_0 \cdot \epsilon_r \cdot \int_0^R \frac{2 \cdot \pi \cdot r \cdot dr}{D_0 - y(P, r)} \quad (3)$$

where C is the capacitance under an applied pressure P , ϵ_0 is the permittivity in vacuum, ϵ_r is the relative permittivity, R is the radius of the electrode, r is the current radius, D_0 is the distance between the electrodes at zero applied pressure and $y(P, r)$ is the deflection at the current radius r when the pressure P is applied.

4. SENSOR DESIGN

For the evaluation of the ceramic capacitive pressure sensors the sensor was designed for the pressure range from 0 to 3 kPa. The test samples were fabricated with the LTCC material Du Pont 951. The thickness of the diaphragm is 100 μm and the diameter of the cavity is 8.4 mm. The diameter of both electrodes is 7.7 mm and the distance between the electrodes is about 70 μm . The thickness of the

electrodes is about 12 μm . The dimensions of the sensor's body are 17.5 \times 12.6 \times 0.8 mm. The thickness of the sensor's body in the area of the cavity is 0.9 mm. The design of the 3D LTCC structure of a ceramic capacitive pressure sensor and the details of the parallel-plate air-gap capacitor are presented in Figure 3. The 3D LTCC structure forms the body of the ceramic sensor, which includes the diaphragm, the cavity and the channel. The channel links the cavity with the inlet tube for the reference pressure. Integrated into the LTCC structure are the two electrodes of the pressure sensor's capacitor and two contact pads. One of the fabricated samples of the ceramic capacitive pressure sensors made as a 3D LTCC structure is shown in Figure 4.

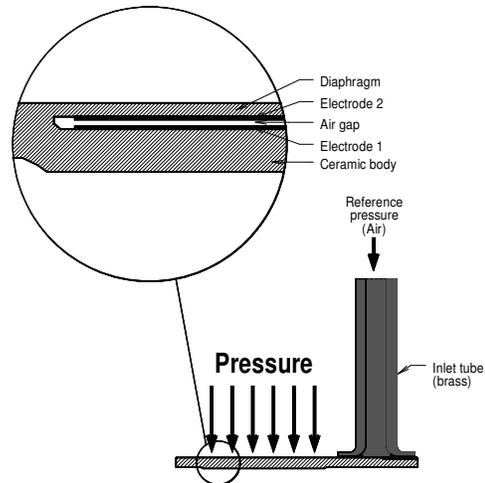


Fig. 3. Schematically presented cross-section of a ceramic capacitive pressure sensor with a detail of the parallel-plate air-gap capacitor (schematic and not to scale)

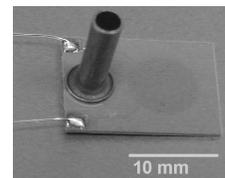


Fig. 4. The ceramic capacitive pressure sensor made as a 3D LTCC structure

5. EXPERIMENTAL

Linearity

The pressure range where the sensor's characteristic is linear (capacitance versus applied

pressure) was defined by the geometry of the diaphragm and mechanical properties of the materials. For good linearity the deflection of the diaphragm (Equation 1) at the maximum applied pressure must be much smaller than the thickness of the diaphragm and the distance between the electrodes. The characteristic of the test samples is perfectly linear in the pressure range from 0 to 5 kPa (Figure 5). In this case the maximum deflection is about 2 μm . The characteristic of the same pressure sensor but for a wider pressure range becomes nonlinear. The maximum deflection of the diaphragm at a pressure of 100 kPa is about 40 μm . The nonlinearity is shown in Figure 6.

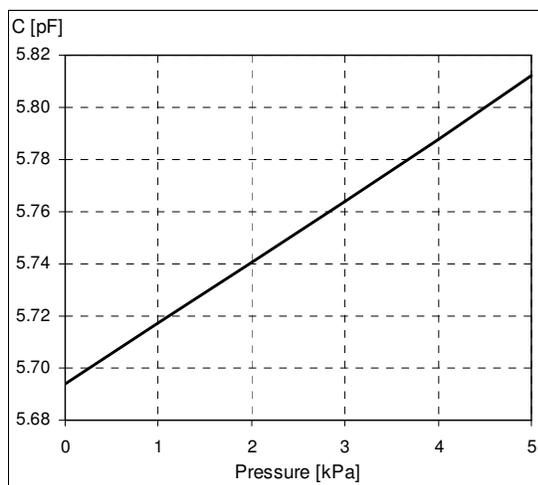


Fig. 5. The capacitance of the ceramic capacitive pressure sensor versus pressure in the range from 0 to 5 kPa

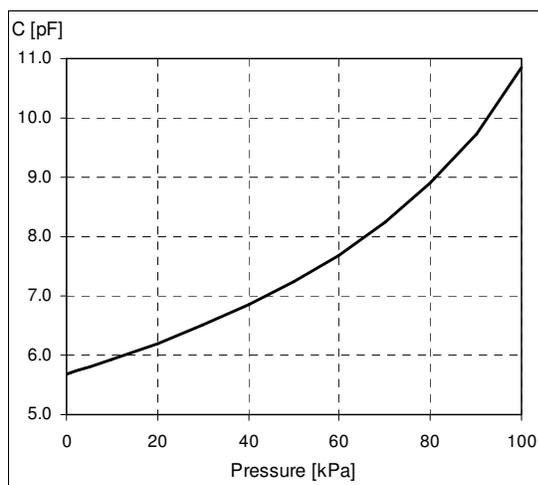


Fig. 6. The capacitance of the ceramic capacitive pressure sensor versus pressure in the range from 0 to 100 kPa

Temperature behaviour

Some of the test samples were tested at different applied pressures and at different temperatures. The temperature dependences of the capacitive pressure sensors are relatively high and may be positive or negative [18]. The relative changes in the initial capacitance of two selected test samples, which have two extreme (maximum and minimum) temperature dependences, versus the different temperatures are shown in Figure 7.

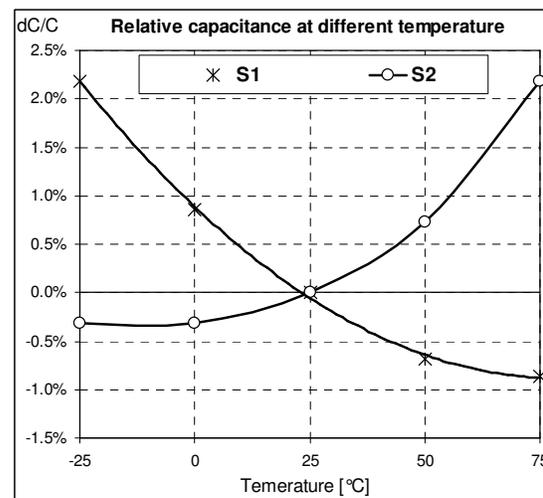


Fig. 7. The capacitances of the ceramic capacitive pressure sensor versus pressure in the range from 0 to 5 kPa

Pressure media

The previous description of the ceramic capacitive pressure sensor neglected the effect of all the additional fringing capacitances, which can be found in the ceramic sensor's body and in the pressure media. In reality the value of the initial capacitance (C_0) includes not only the capacitance of the parallel-plate air-gap capacitor (C_a), but also several additional fringing capacitances, like the capacitance of the ceramic body (C_c) and the capacitance of the pressure media (C_m). The mentioned parallel-plate air-gap capacitance and the additional fringing capacitances are schematically shown in Figure 8. The values of all these capacitances depend on the geometry, the construction and the electrical properties (especially the relative permittivity) of the materials.

The test samples were fabricated with the LTCC material DP 951, which has a relative permittivity of

about 7.8. The relative permittivities (ϵ_r) of some other test materials are presented in Table 1.

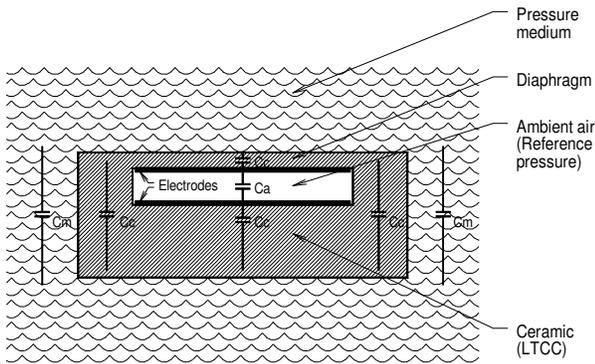


Fig. 8. Schematically presented capacitance of the parallel-plate air-gap capacitor and the additional fringing capacitances of the ceramic capacitive pressure sensor in pressure media (not to scale)

Materials	Relative Permittivity (ϵ_r)
Air	1
Silicon oil	2.5
Water	80

Tab. 2. Relative permittivities (ϵ_r) of the test materials

The test samples were immersed into four different liquid media (air, silicone oil, and deionising water). The initial capacitance (C_0) of the ceramic capacitive pressure sensors were measured after the liquids were stabilized at room temperature (23-25°C).

If the initial capacitance of the ceramic capacitive pressure sensor in air media is the reference value, then the silicone oil media increased the capacitance by about 3%, the absolute ethanol by about 55%, and the deionising water by about 90%.

The influence of reference pressure

The investigated ceramic capacitive pressure sensor was designed as a gauge pressure sensor. In this case the reference pressure is equal to the ambient air (atmospheric) pressure. Therefore, the dielectric between the electrodes of the capacitive pressure sensor is ambient air. The value of the relative permittivity of the air is about 1.0006 at a temperature of 25°C, a relative humidity of 25% and a pressure of 1013 mbar. However, the relative permittivity of the air is not a constant value; it depends on the

temperature, pressure and humidity, as described by equation (4) [19].

$$\epsilon_{r(air)} = \left[1 + \frac{211}{T} \cdot \left(P + \frac{48 \cdot P_s}{T} \cdot H \right) \cdot 10^{-6} \right] \quad (4)$$

where $\epsilon_{r(air)}$ is the relative permittivity of air, T is the absolute temperature (K), P is the pressure of air (mm Hg), P_s is the pressure of saturated water vapour at temperature T (mm Hg), and H is the relative humidity (%). The calculated relative permittivity versus relative humidity of the air at four different temperatures is graphically presented in Figure 9.

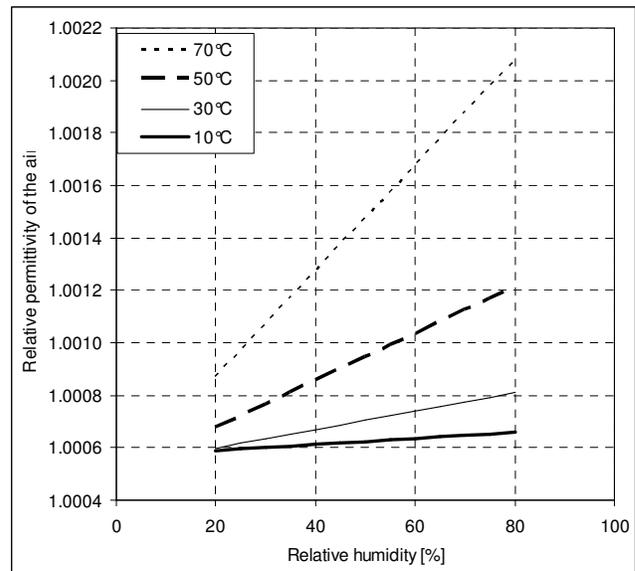


Fig. 9. The relative permittivity of air ($\epsilon_{r(air)}$) versus the relative humidity at different temperatures

The ceramic capacitive pressure sensor was designed to operate in the following ambient conditions: temperature from 10 to 70°C, relative humidity from 20 to 80%, and atmospheric pressure from 980 to 1050 mbar. In these conditions the maximum overall drift of the relative permittivity of the air is up to $+3750 \times 10^{-6}$. The main influence on the permittivity comes from that of the temperature of the air, with a maximum drift of the permittivity up to $+3700 \times 10^{-6}$, followed by the humidity of the air (maximum drift of the permittivity of the air is up to $+3430 \times 10^{-6}$). The different atmospheric pressure has a minor influence on the relative permittivity of the air (maximum drift of the permittivity of the air is up to $+40 \times 10^{-6}$).

ACKNOWLEDGMENTS

The authors wish to thank Mr. Mitja Jerlah (HIPOT-RR) for fabricating the test samples.

This work is part of a joint research project of partners from the University “Politehnica” of Bucharest, Romania, HIPOT-RR, Slovenia, and Jožef Stefan Institute, Slovenia. The project has been supported through a Romania–Slovenia cooperation in science and technology 2008–2009. The financial support of the Romanian National Authority for Scientific Research (ANCS) and the Slovenian Research Agency (ARRS) is gratefully acknowledged.

REFERENCES

- [1] M. Pavlin, D. Belavič, M. Santo Zarnik, M. Hrovat, M. Možek, “Packaging technologies for pressure-sensors”. *Microelectronics international*, 2002, Vol. 19, pp. 9-13.
- [2] N. Maluf, K. Williams, “An Introduction to Microelectromechanical System Engineering”, *Artech House, Inc.*, Norwood, 2004.
- [3] D. Belavič, M. Hrovat, M. Pavlin, M. Santo Zarnik, “Thick-film technology for Sensor Applications”, *Informacije MIDE M*, Vol. 33, No.1, 2003, pp. 45-48.
- [4] U. Partsch, D. Arndt, H. Georgi, “A new concept for LTCC-based pressure sensors”, *Proceedings of the IMAPS/ACerS 2007, 3rd International Conference and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT)*, Denver, Colorado, USA, April 23-26, 2007, pp. 367-372.
- [5] D. Belavič, M. Santo Zarnik, M. Hrovat, S. Maček, M. Pavlin, M. Jerlah, J. Holc, S. Drnovšek, J. Cilenšek, M. Kosec, “Benchmarking different types of thick-film pressure sensors”, *Proceedings of the IMAPS/ACerS 2007, 3rd International Conference and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT)*, Denver, Colorado, USA, April 23-26, 2007, pp. 278-285.
- [6] R. Puers, “Capacitive sensors: when and how to use them”, *Sensors and Actuators A*, Vol. 37, 1993, pp. 93-105.
- [7] T. Thelemann, H. Thust, M. Hintz, “Using LTCC for microsystems”, *Microelectronics International*, Vol. 19, No. 3, 2002, pp. 19-23.
- [8] L.J. Golonka, A. Dziedzic, J. Kita, T. Zawada, “LTCC in microsystem application”, *Informacije MIDE M*, Vol. 32, No.4, December 2002, pp. 272-279.
- [9] M.R. Gongora-Rubio, P. Espinoza-Vallejos, L. Sola-Laguna, J.J. Santiago-Aviles, “Overview of Low Temperature Cofired Ceramics tape technology for meso-system technology (MsST)”, *Sensors & Actuators A*, Vo. 89, 2001, pp. 222–241.
- [10] J.Kita, R.Moos, “Development of LTCC-materials and Their Applications: an Overview”, *Informacije MIDE M*, Vol. 38, No. 4, 2003, pp. 219-224.
- [11] T. Maeder, C. Jacq, H. Briol, P. Ryser, “High-strength Ceramic Substrates for Thick-film Sensor Applications”, *Proceedings of the 14th European Microelectronics and Packaging Conference*, Frieddrichshafen, Germany, 2003, pp. 133-104.
- [12] D. Belavič, M. Santo Zarnik, M. Jerlah, M. Pavlin, M. Hrovat, S. Maček, “Capacitive thick-film pressure sensor: material and construction investigation”, *Proceedings of the XXXI International Conference of IMAPS Poland 2007*, Rzeszów, Krasiczyn, Poland, pp. 249-253, September 2007, 23-26.
- [13] M. Yamada, T. Takebayashi, S. I. Notoyama, K. Watanabe, “A Switched-Capacitor Interface for Capacitive Pressure Sensors”, *IEEE Transactions on Instrumentation and Measurement*, Vol. 41, No. 1, February 1992, pp. 81-86.
- [14] C. B. Sippola, C. H. Ahn, “A thick film screen-printed ceramic capacitive pressure microsensor for high temperature applications”, *Journal of Micromechanics and Microengineering*, Vol. 16, 2006, pp. 1086-1091.
- [15] D. Belavič, M. Santo Zarnik, S. Maček, M. Jerlah, M. Hrovat, M. Pavlin, “Capacitive pressure sensors realized with LTCC technology”, *Proceedings of the 31st International Spring Seminar on Electronics Technology (ISSE 2008), Reliability and life-time prediction*, Piscataway: IEEE, Budapest, Hungary, 7-11 May, 2008. pp. 271-274.
- [16] M. Santo Zarnik, D. Belavič, S. Maček, “Case study of a miniature LTCC-based capacitive pressure sensor for applications in the low pressure range”. *Proceedings of the 44th International Conference on Microelectronics, Devices and Materials and the Workshop on Advanced Plasma Technologies*, September 17. - September 19. 2008, Fiesa, Slovenia, pp. 153-158.
- [17] C. Ionescu, P. Svasta, C. Marghescu, M. Santo Zarnik, D. Belavič, “Study on optimization of capacitive pressure sensor using coupled mechanical-electric analysis”, *Proceedings of the 32nd International Spring Seminar on Electronics Technology (ISSE 2009), Hetero system integration, the path to new solutions in the modern electronics*, Denver: IEEE, Brno, Czech Republic, May 13-17, 2009, 6 p.
- [18] D. Belavič, M. Santo Zarnik, M. Hrovat, S. Maček, M. Kosec, “Temperature behaviour of capacitive pressure sensor fabricated with LTCC technology”, *Informacije MIDE M*, Vol. 38, No. 3, 2009, pp. 191-196.
- [19] I. Nathan, “Chemical Sensors”, <http://ee.asc3.uakron.edu/ida/sensors/chapter8.ppt>